

The effect of operating parameters in the Stirling cryocooler [☆]

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Abstract

This paper presents design, manufacturing process and test results in the optimum operating condition for the free piston free displacer (FPFD) type Stirling cryocooler designed and manufactured by Korea Institute of Machinery and Materials. FPFD Stirling cryocooler is currently under development for cooling infrared detector. The compressor in the Stirling cryocooler uses opposed linear motors to drive opposed pistons. The performance of FPFD Stirling cryocooler is evaluated as a function of charging pressure and operating frequency. In general, as the charging pressure is increased, optimum-operating frequency of the compressor is increased but resonant frequency of the displacer is almost constant. The prototype has achieved no load temperature of 49 K and cooling power of 0.5 W at 72 K.

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1. Introduction

The small cryocooler is being widely applied to the areas of infrared detector, superconductor filter, satellite communication, and cryopump.

The Stirling cycle coolers were first introduced to the commercial market in the 1950s as small single cylinder air liquefier and a cryocooler for infrared sensors to about 80 K. The compressor in the Stirling cryocooler is a valveless type. In order to provide high power densities and keep the system small, the average pressure is typically in the range of 1–3 mPa and frequencies are in the range of 20–60 Hz [1].

Free-piston Stirling engines acting as power systems were invented by William Beale in the early 1960s and have been in continuous development since that time at sunpower. The first development of linear free-piston Stirling cryocooler was accomplished at the Philips Laboratories, Eindhoven. Haarhuis [2]. Later de Jonge [3]

presented a classic paper related to the theoretical analysis of free-piston Stirling machines.

Another significant miniature linear Stirling cryocooler is the unit developed by Dr. G. Davey of Oxford University. Progress in the development of this interesting machine was reported by Orlowsky and Davey [4].

Over the past decade and a half there has been rapid development of miniature free piston free displacer (FPFD) Stirling cryocoolers, mainly for military and space applications. Most of them are designed for a cooling capacity of about 1 W or lower at 80 K. There has been a distinct preference for the split configuration as opposed to an integral design with the piston being driven by a linear motor, usually of the moving coil type.

The cryocooler working on the Stirling cycle are characterized by high efficiency, fast cool down, small size, light weight, low power consumption and high reliability. Typical applications of the Stirling cryocooler are cooling of HTS devices, and cooling of detectors, for example, X-ray, Gamma ray, infrared sensors and computer chips [5].

For these reasons, FPFD Stirling cryocooler is widely used not only tactical infrared imaging camera but also medical diagnostic apparatus.

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We have been developing as a target of this use a split type FPDF Stirling cryocooler with a compressor which has dual opposed pistons driven by linear motors.

In this paper, for the given FPDF Stirling cryocooler, design, manufacturing process and experimental method to find optimal operating conditions are described and experimental results on the performance of Stirling cryocooler according to the variations of the operating pressure and frequency are presented.

2. Design and manufacturing of the stirling cryocooler

Fig. 1 shows the schematic view of the FPDF Stirling cryocooler. FPDF Stirling cryocooler consists of two major parts; linear compressor module and expander module.

Linear compressor consists of linear motor, inner and outer yoke, permanent magnet, coil, cylinder, piston and spring, and expander module consists of displacer, regenerator in the displacer, displacer cylinder, spring and heat exchanger.

Major factors in design process to improve performance of FPDF Stirling cryocooler are permanent magnet, coil characteristics, materials of yokes and magnet, and in operating process are charging pressure, volume of the split tube and operating frequency.

Table 1 shows the main specifications of the FPDF Stirling cryocooler we have developed. Table 2 shows the favorable structure to satisfy specifications of the

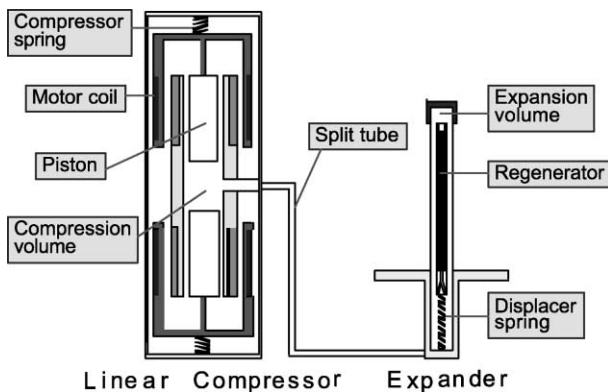


Fig. 1. Schematic diagram of the FPDF Stirling cryocooler.

Table 1
Performance of FPDF Stirling cryocooler

Items	Specifications
Refrigerating cycle	Stirling cycle
Cooling power	0.5 W at 77 K
MTTF	5000 h
COP	0.03
Cool-down time	5 min
Configuration	Split linear

Table 2
Structure of Stirling cryocooler

Items	Requirements	Structure
Drive mechanism	Oil free	Free piston free displacer
Motor	Controllability of frequency and force	Linear motor
Bearing	Low-contact high centering	Coil spring fine gap seal
Control	Cooling power control	Displacement control

Table 3
Dimensions and materials of the FPDF Stirling cryocooler

Items	Materials	Dimensions (mm)
Piston	SUS 304	12 × 20
Displacer	SUS 304	5.8 × 70
Regenerator	SUS 304	#300
Magnet	NdFeB	35 × 20
Fine gap (radius) in compressor		15 μm
Fine gap (radius) in expander		30 μm

FPDF Stirling cryocooler. The reason why we have chosen a split type and also a type of a linear motor driven compressor is that this type of a cryocooler had been considered to be able to take a fully oilless configuration and to fit the requirement of a long life [6,7].

Table 3 shows dimensions and materials of piston, displacer, regenerator and magnet in the Stirling cryocooler. Helium is used as the working fluid in the Stirling cryocooler cycle because of its ideal gas properties, its high thermal conductivity, and its high ratio of specific heats.

Fig. 2 is the flow chart for design, manufacturing, fabrication and test of the FPDF Stirling cryocooler. Detailed analysis of FPDF Stirling cryocooler requires calculation of many nonlinear fluid flow, heat transfer, and thermodynamic effects. Such detailed analysis is, however, very cumbersome. Basic design is based on simplified linear analysis. Basic analysis for design of the Stirling cryocooler was performed by Schmidt analysis method and heat loss evaluation.

A moving coil type linear motor consists of permanent magnets as a stator, a coil-wrapped nonmagnetic structure and an iron core as a pathway for magnetic flux. The variation of mover position and the consequent changes of coil flux path affect the coil inductance because of unbalanced magnetic circuit. The variations of the coil inductance and thrust with displacement of the actuator decrease the advantage of moving coil linear motor, such as a high degree of linearity and controllability in the force and motion [8].

Fig. 3 illustrates magnetic circuit generated by the NdFeB permanent magnet magnetized radially, coil, inner and outer yokes in the linear motor.

Fig. 4 shows distribution of magnetic flux density in the air gap between NdFeB magnet and outer yoke

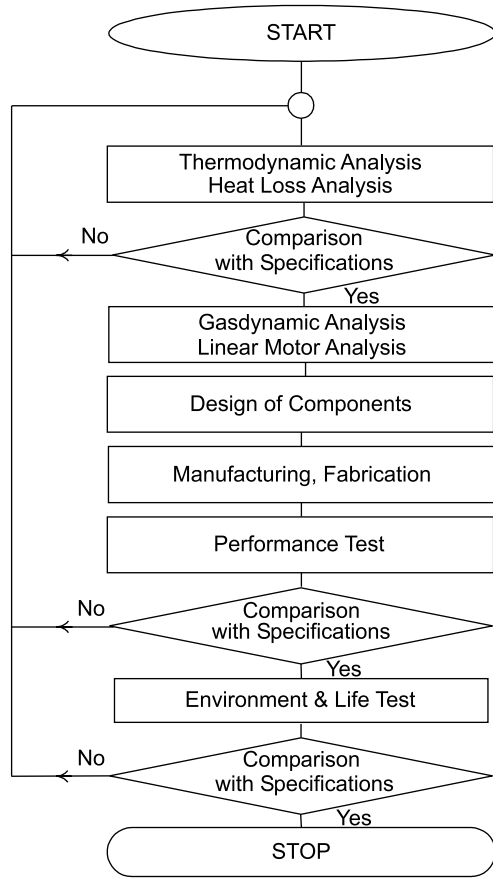


Fig. 2. Design and test flow chart.

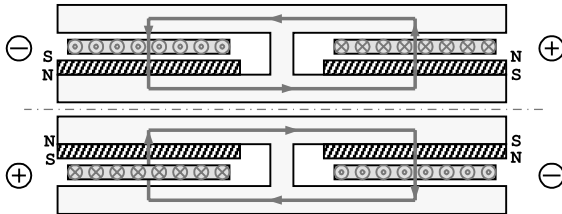


Fig. 3. Permanent magnet and inner/outer yoke.

made of iron. Mean magnetic flux density in the air gap was 0.48 T.

Fig. 5 shows schematic diagram of compressor without coil spring. Single piston oscillator is associated with a buffer volume V . The motion of the moving masses (pistons) may be described by the classical spring–mass–damper equation [9,10]:

$$M_c \ddot{x} + c \dot{x} + k_g x = B_g l i \quad (1)$$

where M_c is mass of piston, c is damping constant, k_g is gas spring constant, B_g is magnetic flux density, i is the zero-to-peak current supplied to the motor, l is the length of the coil, ω is angular velocity and t is time.

Helium gas at room temperature under moderate pressure can be considered as a perfect gas and the gas spring constant is given by [11]

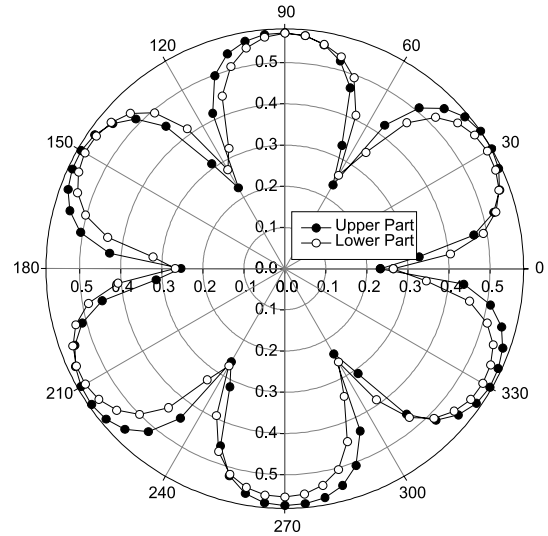


Fig. 4. Distribution of magnetic flux density in the air gap.

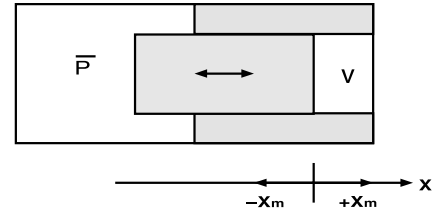


Fig. 5. Schematic diagram of compressor without coil spring ($\bar{P}$: mean pressure, V : buffer volume, X : actual stroke, X_m : maximum mean stroke).

$$k_g = \frac{-\alpha \bar{P} A_c^2 x}{A_c (x_m - x) + V} \quad (2)$$

where A_c is the cross-section of the piston and α is a parameter which depends on the type of compression: $1(\text{isothermal}) \leq \alpha \leq \gamma(\text{adiabatic})$.

For small strokes and assuming the piston displacement is almost sinusoidal, the resonant frequency f_c without the mechanical spring and f_r with the mechanical spring are respectively given by

$$f_c = \frac{1}{2\pi} \sqrt{\frac{\alpha \bar{P} A_c^2}{(A_c x_m + V) M_c}} \quad (3)$$

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k + \alpha \bar{P} A_c^2 / (A_c x_m + V)}{M_c}} \quad (4)$$

Fig. 6 shows current variation with different charging pressure. When the compressor is operated by resonant frequency, the current in the compressor is lowest. At the low frequency, the cooler response is dominated by the characteristics of the mechanical spring, but at the

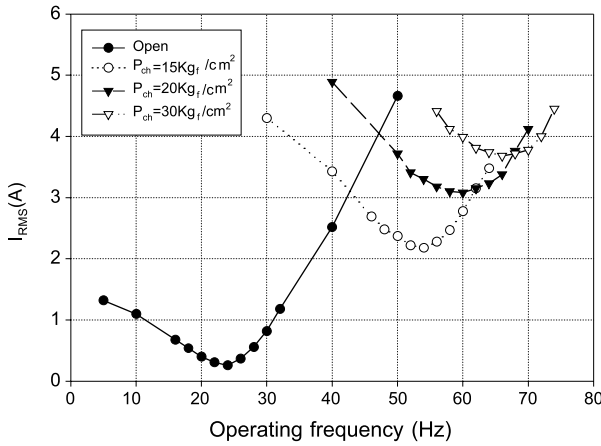


Fig. 6. Current variation with different charging pressure.

high frequency, the cooler is controlled by the characteristics of the gas [12,13]. As the charging pressure was increased, current and resonant frequency of the compressor was increased because of the gas spring effect.

Resonant frequency of the displacer is simply given by

$$f_d = \frac{1}{2\pi} \sqrt{\frac{k_d}{M_d}} \quad (5)$$

where f_d is resonant frequency of the displacer, k_d is mechanical spring constant of the displacer and M_d is the mass of the displacer.

Phase difference of the piston and the displacer is described as Eq. (6); in general, optimum phase difference is 45° in the FPDF Stirling cryocooler [3].

$$\tan \psi_{dr} = \frac{M_d(\omega_d^2 - \omega^2)}{C_{dd}A_d\omega} \quad (6)$$

where ψ_{dr} is phase difference of the piston and the displacer, ω_d is resonant angular frequency of the displacer, ω is operating angular frequency, C_{dd} is constant by

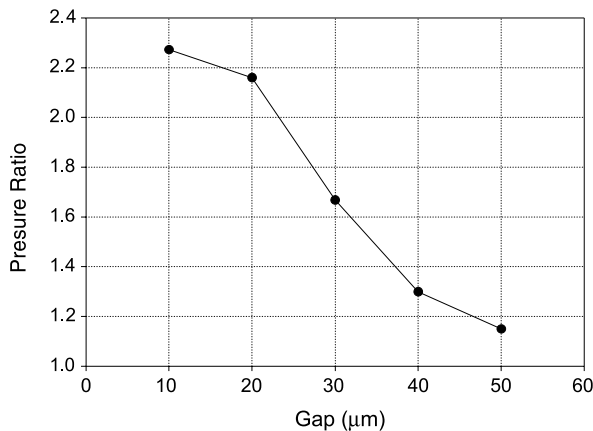


Fig. 7. Pressure ratio with different gap between cylinder and piston.

friction and flow resistance, and A_d is cross-section of the displacer.

Pressure ratio of the linear compressor is very significant factor for design for the FPDF Stirling cryocooler. Pressure ratio is affected by compression and expansion volume and the gap between cylinder and piston. Compression and expansion volume is determined by thermal analysis and resonant frequency.

The results of the pressure ratios with different gap between cylinder and piston are shown in Fig. 7. As the gap between cylinder and piston was increased, pressure ratio of the compressor was decreased.

3. Experimental procedure

Fig. 8 shows the schematic diagram of the experimental apparatus of the FPDF Stirling cryocooler. Piezo-electric dynamic pressure sensors were used to monitor pressure oscillations at the outlet of the compressor and buffers of each end. Linear variable differential transformers (LVDTs) were provided at each end of the compressor for displacement measurement of the pistons. A load heater and a silicon-diode thermometer were attached to the cold head. A manganin resistance heater was provided at the cold end to measure the cooling capacity. After attaching those, the cold end of the Stirling cryocooler was wrapped by multi-layer insulation (MLI) for radiation shield, and the apparatus of the Stirling cryocooler except the component of the room temperature region was connected to the vacuum flange. During the experiment, a vacuum chamber was connected to the high vacuum pump under a pressure of 10^{-5} Torr.

The high vacuum pump system consists of a rotary roughing pump, diffusion pump and vacuum gauges [14,15].

The following tests had been undertaken for the experimental analysis of the Stirling cryocooler:

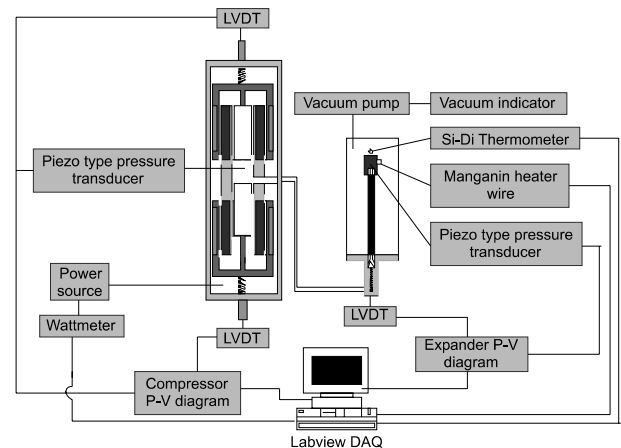


Fig. 8. Experimental apparatus of the cryocooler.

- (1) variation of the natural frequency in the compressor and the displacer with the charging pressure;
- (2) variation of current, power and pressure in the compressor with applied voltage;
- (3) cool-down characteristics and required time to 77 K in the cold end with applied voltage;
- (4) cool-down characteristics and cooling capacity with operating frequency.

4. Experimental results and discussion

From Eqs. (4) and (5), resonant frequency of the compressor is mainly affected by charging pressure, but resonant frequency of the displacer is affected by mass and mechanical spring constant of the displacer [16–18]. Fig. 9 displays variation of the resonant frequency in the compressor and the displacer with the charging pressure. As the charging pressure was increased, resonant frequency of the compressor was increased, but resonant frequency of the displacer was almost constant, 67 Hz. Considering resonant frequency of the displacer, optimum operating frequency of the compressor was 50 Hz and the charging pressure of the FPDF Stirling cryo-cooler was the most adequate at 12–14 kg_f/cm².

Figs. 10 and 11 show pressure variation of compressor and current and input power variation with applied voltage, respectively. The charging pressure was 12.5 kg_f/cm² and operating frequency was 50 Hz. Sustaining time in the low pressure region was 20% longer than in the high pressure region. And pressure amplitude was about 3 kg_f/cm² at the maximum applied voltage of 10 V. As the charging pressure was increased, input power and current was increased linearly and input power and current was 36 W, 3.6 A, respectively.

Figs. 12 and 13 show cool-down characteristics and required times to 77 and 100 K in the cold end with applied voltage, respectively. As the applied voltage was increased, cool-down time to 77 K was shortened and no load temperature was decreased.

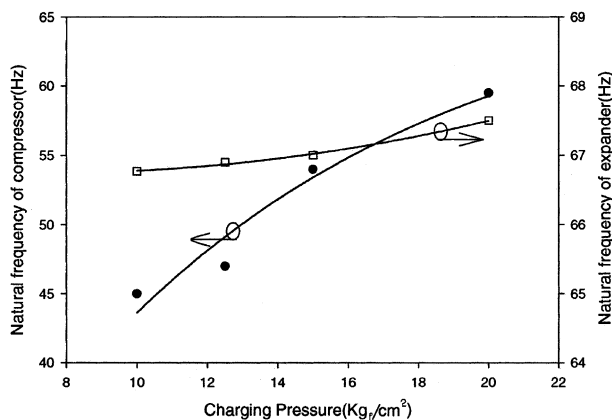


Fig. 9. Resonant frequency of compressor and displacer.

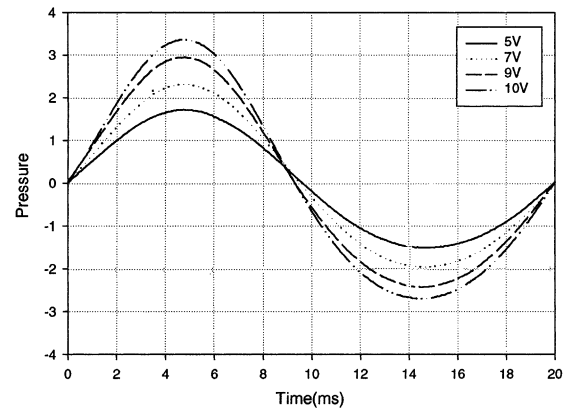


Fig. 10. Pressure variation of compressor with applied voltage (operating frequency: 50 Hz).

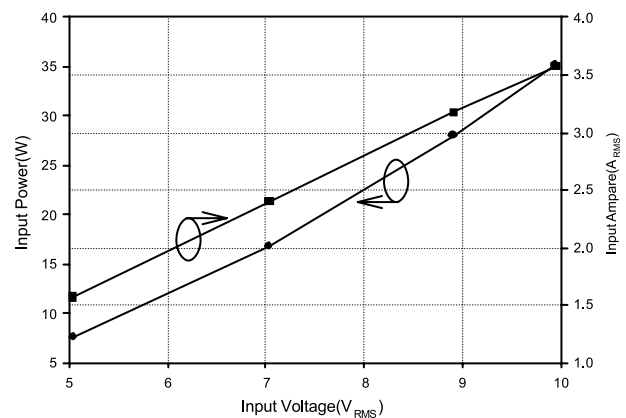


Fig. 11. Current and power variation with applied voltage.

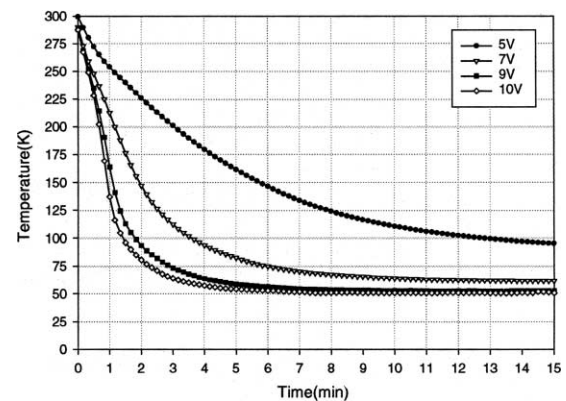


Fig. 12. Cool-down characteristics with applied voltage.

Figs. 14 and 15 show cool-down characteristics and cooling capacity with the operating frequency at the ambient temperature 295 K, respectively. At the operating frequency of 50 Hz, cool-down time was the shortest, and cooling capacity was maximum. The shortest cool-down time from the room temperature of 295 to

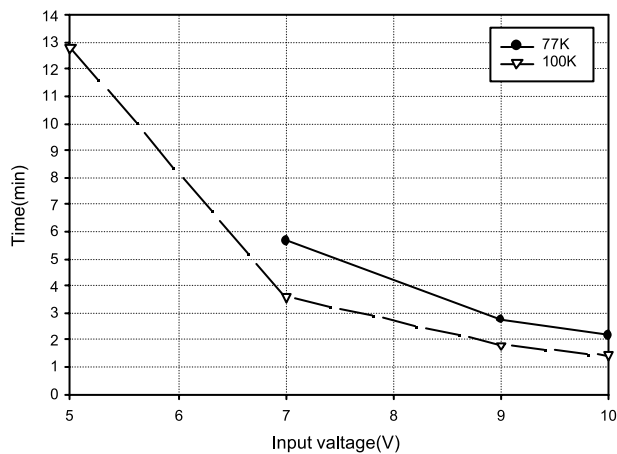
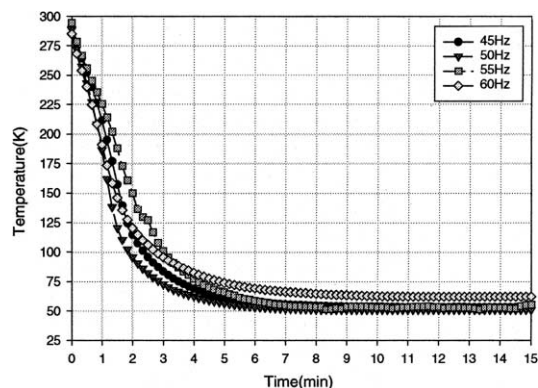
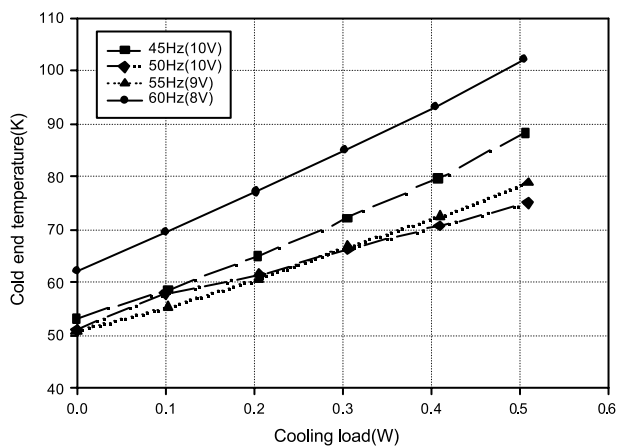


Fig. 13. Required time with applied voltage (77, 100 K).

Fig. 14. Cool-down characteristics (charging pressure: 14 kgf/cm²).Fig. 15. Cooling capacity (charging pressure: 14 kgf/cm²).

77 K was about 2 min and the lowest temperature was 49 K. And a maximum cooling capacity at the cold end was 0.5 W at 72 K.

From Fig. 16, coefficient of performance (COP) of Stirling cryocooler was highest at 50 Hz.

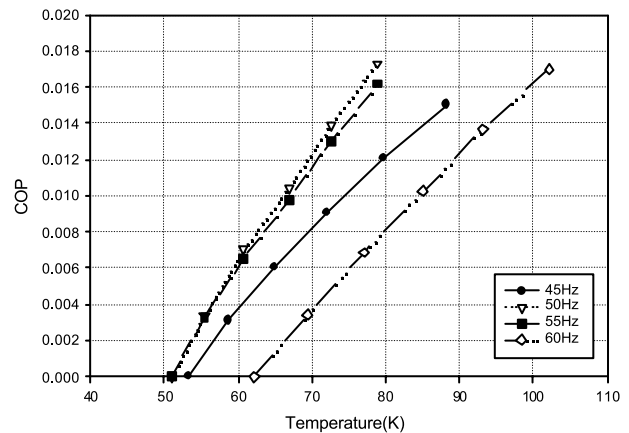


Fig. 16. COP with operating frequency.

5. Conclusions

We have undertaken the development of a FPFD Stirling cryocooler using clearance seal for contactless operation. The performance of FPFD Stirling cryocooler is affected by operating parameters such as charging pressure, operating frequency, length of the split tube and so on. In this paper, design and manufacturing processes of the Stirling cryocooler was described, and the effects of the charging pressure and operating frequency were presented and evaluated by experiments.

At the low frequency, the cooler response was dominated by the characteristics of the mechanical spring, but at the high frequency, the cooler was controlled by the characteristics of the gas spring. As the charging pressure was increased, current and resonant frequency of the compressor were increased because of the gas spring effect. When the compressor was operated by resonant frequency, the current in the compressor was lowest.

As the charging pressure was increased, resonant frequency of the compressor was increased, but resonant frequency of the displacer was almost constant.

As the applied voltage was increased, cool-down time to 77 K was shortened and no load temperature was decreased.

When the resonant frequency of the compressor was about 50 Hz, at the operating frequency of 50 Hz, cool-down time was the shortest, and cooling capacity was maximum.

The shortest cool-down time from the room temperature of 295 to 77 K was about 2 min and the lowest temperature was 49 K. And a maximum cooling capacity at the cold end was 0.5 W at 72 K, and COP of Stirling cryocooler is highest at 50 Hz.

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